

Advances in the Metallurgy and Applications of ADI

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Abstract

The excellent property combination of ADI has opened new horizons for cast iron to replace steel castings and forgings in many engineering applications with considerable cost benefits. Thanks to the extensive research efforts made over the past few years, new processing techniques have opened even more opportunities for this very prospective material to acquire better combinations of strength, ductility, toughness, wear resistance as well as machinability.

This review analyses the key features of those novel processing techniques and the resulted new applications of ADI. The survey firstly discusses the possible strengthening mechanism of ADI with special emphasis on the TRIP phenomena, associated with the deformation of ADI. Strength and toughness properties could be improved through the development of:

- Ausformed ADI; where mechanical processing component was added to the conventional heat treatment as a driving force to accelerate the rate of stage I austempering.
- Squeeze cast ADI; where superior quality ADI castings were produced through squeeze casting of molten iron in a permanent mold, followed by in-situ heat treatment of the hot knocked-out castings in the austenite range followed by normal austempering in a salt bath.
- Two step austempering to achieve finer ausferrite at higher undercooling during austempering treatment followed by austempering at higher temperature where higher austenitic carbon is promoted.

The machinability and ductility of ADI may be considerably enhanced through the development of dual phase microstructures (ferrite + ausferrite or ferrite-martensite by partial austenitization in the ($\alpha + \gamma + \text{graphite}$) region followed by normal austempering.

The abrasion resistance could be remarkably increased through the development of:

- Carbide ADI-ductile iron containing carbides subsequently austempered to form ausferritic matrix with an engineered amounts of carbides
- Bainitic/martensitic (B/M) ADI containing less expensive alloying elements such as Si and Mn in the range of 2.5 - 3.0%

This report discusses as well the recent trials to produce thin-wall ADI castings.

Keywords

ADI; Austempered Ductile Cast Iron; Heat Treatment; Ausforming; Austempering

Introduction

The as-cast mechanical properties of ductile iron can be significantly improved through an austempering heat treatment. This has led to the birth of a new member of the cast iron family; the austempered ductile iron (ADI), with its unique microstructure; spheroidal graphite in an ausferritic matrix [1].

The austempering transformation in ADI can be described as two-stage reaction:

Stage I Reaction: $\gamma_c \rightarrow \alpha + \gamma_{HC}$
(toughening)

Stage I Reaction: $\gamma_{HC} \rightarrow \alpha + \epsilon -$
carbides (embrittlement)

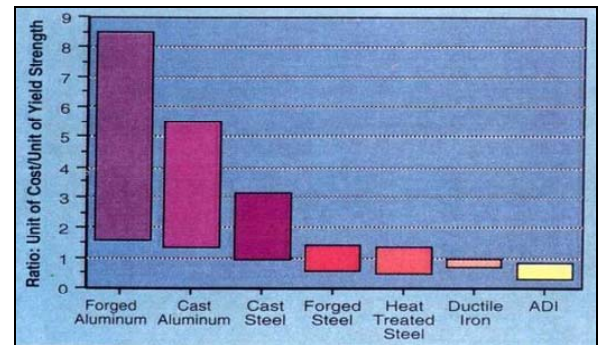
The morphology of the final two-phase matrix microstructure is determined by the number, shape and size of the initially formed ferrite platelets in the first stage austempering reactions. The control of this stage of transformation will, therefore, ultimately control the final microstructure and mechanical properties. The rate of ferrite formation during stage I austempering may be controlled by chemical, thermal or mechanical processing variables.

Since the announcement of the first production of ADI in the late decades of the last century, a worldwide explosion in research started, which provided a sound foundation for expanding the production of this prospective material in many industrialized countries during the 1990's and beyond. By the turn of the century, the ADI market had begun to rapidly accelerate from a modest beginning in the early 1970's to an estimated worldwide production level of 300,000 tons by the end of the year 2010 [2-4].

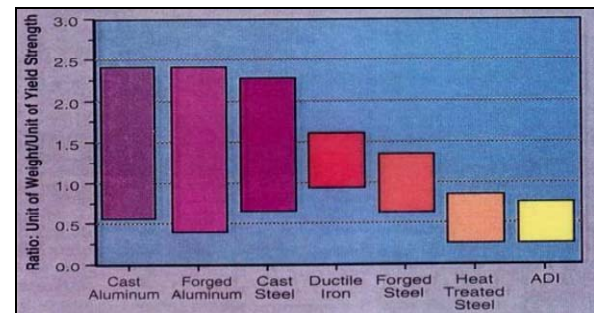
The mechanical properties of ADI depend on a number of interlinked factors, including primarily the austenitizing and austempering temperatures and times together with the as-cast microstructure, the composition and the section size. Of these, the austempering temperature is the most important.[5]. These variations in properties can be related to the changes in microstructure. At low austempering temperatures, an acicular (needle-like) ferritic phase is formed with only a small amount of retained austenite. At the very lowest austempering temperatures, the structure may also contain some martensite. This type of microstructure can provide high tensile strength and hardness but only limited ductility and poor machinability. With increased austempering temperatures, the ferrite becomes coarser with increased amounts of retained austenite (up to ~40%); with a typical "ausferrite" structure. This results in a substantial increase in ductility and machinability with a reduction in strength and hardness.

Once the austempering temperature exceeds a certain value (typically 375-380°C), the stage II reaction occurs very rapidly, resulting in a reduction in the retained austenite and a corresponding decrease in ductility. The unique properties of ADI are closely related to the retained austenite content which is controlled mainly by the austempering temperature and time.[6]

Thanks to the extensive efforts made over the past few years, new processing techniques have opened even more opportunities for this prespective material to acquire better combinations of strength, ductility, toughness, wear resistance as well as machinability. The selection of ADI is usually based on a wide range of factors such as properties, density, cost and others. Figure 1 demonstrates the competitive edge of ADI compared with forged steel and cast and forged aluminum alloys [7].



(a)



(b)

FIG. 1 COMPARISON OF THE COST (A) AND WEIGHT (B) PER UNIT OF YIELD STRENGTH FOR DIFFERENT MATERIALS [7]

Strengthening Mechanism of ADI

ADI has found and still is finding so many applications, where it proved to be an excellent engineering materials. The practice of ADI production seems to be ahead of the theory. The strengthening mechanisms of ADI are still under investigation. The main constituents of ADI matrix are acicular ferrite and carbon enriched austenite (with the possibility of some martensite formations at low austempering temperatures), both main constituents are of low or medium strength. The "mystery" of the high strength of ADI, and how it may result from these constituents have been earlier related to the precipitation hardening arising from the formation of very tiny precipitates such as M_6C type carbides and others[8]. The density of these precipitates, however, seems to be too low to result in such superior strength properties. Recently [9], extensive use of TEM has shed more light on the strengthening mechanisms of the main structural constituents of ADI, Fig. 2. The strengthening mechanism of ferrite was related to strain hardening caused by very high dislocation density, accompanied by high density very small dislocation loops. In the same time austenite strengthening is caused by solution hardening mechanism supported by grain refining due to twinning, which results in some extra

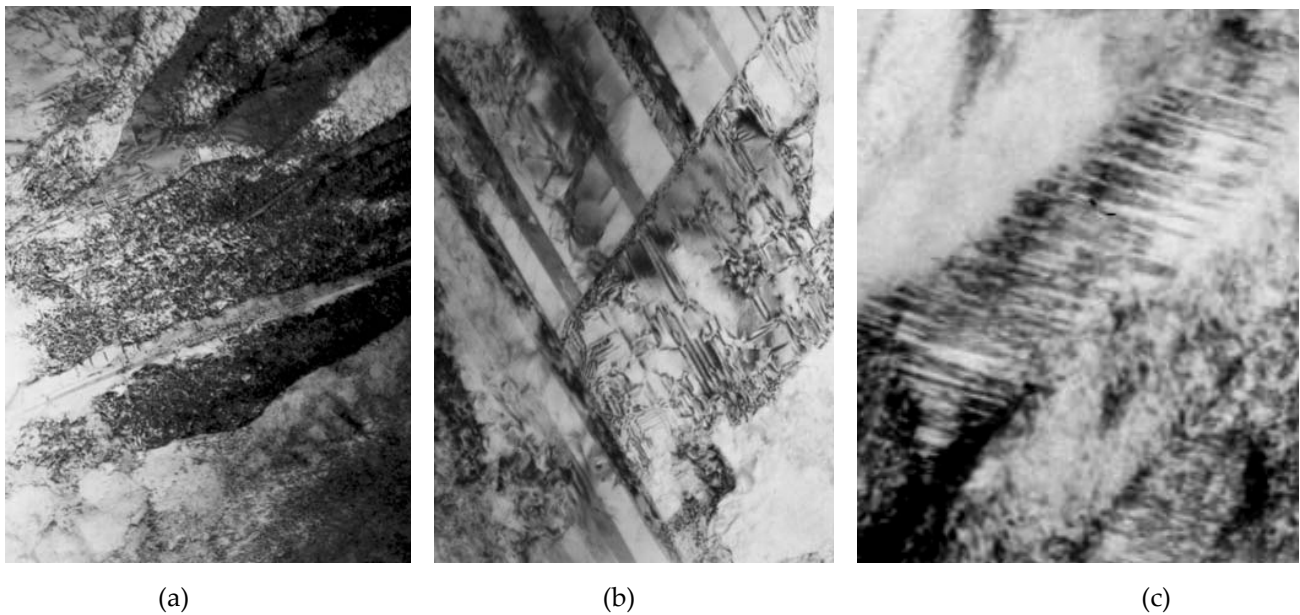


FIG. 2 TEM MICROGRAPHS OF ADI STRUCTURAL CONSTITUENTS: (a) FERRITE NEEDLE (X22,000) SATURATED WITH DISLOCATIONS AND DISLOCATION LOOPS.(b) AN AUSTENITE GRAIN (X35,000) WITH CHARACTERISTIC CONTRAST FROM TWINS AND STACKING FAULTS.(c) DISTORTED MARTENSITE (X140,000) WITH VERY THIN MICTOTWINS [9]

coherent grain boundaries. Moreover, stacking faults representing obstacles for dislocation movement may play some strengthening role.

Moreover, the austenite to martensite transformation at low austempering temperature is accompanied with high lattice distortion and consequently high strain energy. The martensite grains would be divided into a very large number of ultra thin microtwins. The resulting huge amount of coherent grain boundaries will impede the dislocation movement.

Strain Hardening of ADI

Short treatment times lead to inferior mechanical properties due to the presence of untempered martensite. The same trend is produced with the combination of long times and high austempering temperatures, in this case as a result of austenite decomposition into ferrite plus coarse carbides that takes place during the heat treatment. At low austempering temperatures ($\sim 300^\circ\text{C}$), the austenite is plastically stable due to the higher C-content and to the finer distribution of this phase in the microstructure ($V_\gamma \leq 25\%$). The bainitic ferrite and the austenite contribute in this case to the proof stress of the material and the increase of the austenite volume fraction has a beneficial effect on toughness. As the austempering temperature increases, the increased V_γ has two different effects: a decrease in C-content and a coarser morphology of this phase [10].

At higher austempering temperatures (above 370°C), V_γ is usually higher than 25% and the proof stress is controlled by the austenite, which is distributed in larger interconnected areas, and the toughness is defined by the stability of this phase, mainly due to the C-content. The ductility may be remarkably enhanced by the TRIP effect. The TRIP effect (Transformation Induced Plasticity), increasing the work hardening, produces a change in the slope of the Holloman equation.

In recent work [11, 12], cold rolled ADI flat tensile specimens were prepared along the rolling direction and the specimens were subjected to uniaxial tensile test. From the \ln true stress vs \ln true strain curve shown in Fig. 3, it is evident that the data are fitted by two interesting straight lines over the entire range of strain. At plastic strain $\epsilon = 0.0094$ there is an obvious increase in slope of the straight line fitting the data corresponding to the strain hardening exponent "n". This increase was previously observed [10,13] in the alloyed ADI, which means that the Holloman equations, constructing the relationship between true stress and true strain ($\sigma = k \epsilon^n$) is not followed. The change in slope of the $\ln \sigma - \ln \epsilon$ representation can be associated with TRIP effect. Figure 4 shows the instantaneous n during the tensile testing. The instantaneous n (n^*) is the n-value at a given strain based on the Holloman equation where $n^* = d \ln \sigma / d \ln \epsilon$. This value is determined from the true stress - true strain curve. As shown from Fig. 4, n^* increase is

associated with the strain-induced martensitic transformation during the tensile test. The generated strain by the volume expansion accompanying the martensitic transformation stimulates new martensitic transformation resulting in the increase in the instantaneous n -value with strain. As a consequence of changes in the structure in the course of tensile deformation, it is believed that the initial segment of $\ln \sigma$ versus $\ln \epsilon$ corresponding to the lower plastic strain (Fig. 3) is characterized by the plastic deformation of the retained austenite. At higher strains, as previously reported, the deformation process is modified by the formation of strain induced martensite, which takes place when the deformation of austenite has been exhausted [12].

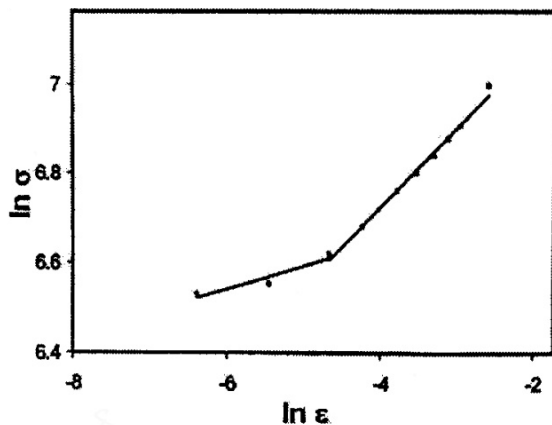


FIG. 3 LN TRUE STRESS VERSUS LN TRUE STRAIN [12]

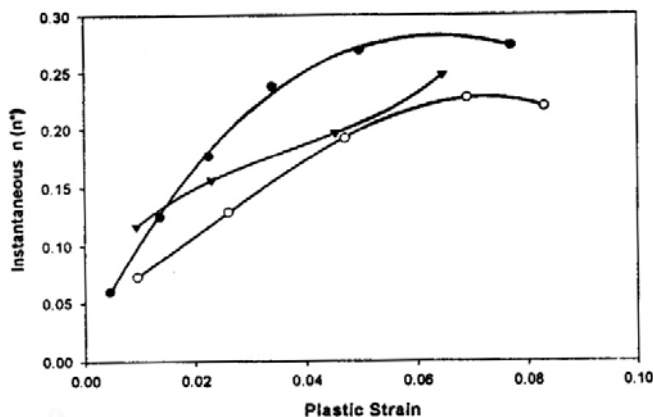


FIG. 4 VARIATION OF INSTANTANEOUS VALUE OF n WITH PLASTIC STRAIN [12]

The difference between the two lines in Fig. 3 can estimate the energy consumed in the TRIP process [10]. The lower the C-content of the austenite, the smaller is the strain necessary to produce the mechanical transformation of the austenite and the smaller is the energy consumed in TRIP. Two types of martensite induced by deformation have been reported [10]. The first is of the lath type which

nucleates at twin boundaries or twin intersection; the second has a plate morphology and seems to form in regions affected by the homogeneous precipitation during the austempering treatment of quasi-coherent epsilon carbides in austenite. This latter martensite is of tempered type, containing epsilon carbides of sizes larger than those found in the parent austenite before deformation.

Improved toughness of ADI results from:

- reduced ferrite particle size
- increased carbon content in the retained austenite, which increases the strain hardening ability and strain hardening coefficient
- stability of the retained austenite [14]

Formation of strain induced martensite is known to enhance the toughness in TRIP steels. In ADI, due to the high C-content, the martensite formed is brittle and it is debatable if the formation of strain induced martensite can improve the toughness. The contribution of strain induced martensite to the toughness of ADI has been recently discussed [15]. The martensite containing ADI can be visualized as fiber reinforced ductile material. Even if the fiber is brittle, it will not make the composite brittle, as long as the fiber is shorter than a critical length, as it will not be loaded to its maximum strength and will not, therefore, fracture. According to this argument, if the retained austenite regions are not massive, then only very short-length of thin martensite will form and will improve the toughness of ADI.

Thus, ADI austempered at lower temperature and having finer ausferritic structure should benefit from the martensite formation, while that treated at higher temperatures and consisting of massive retained austenite together with coarse ferrite will not. The retained austenite in upper bainite can easily transform to strain induced martensite [16].

Increasing the cold rolling (CR) reductions, the amount of retained austenite (γ_r) was decreased due to partial transformation of γ_r to martensite, Figs. 5 and 6 indicate that the amount of mechanically generated martensite increases with increasing the CR reduction [n].

As can be seen from Figures 7 and 8, the elongation and impact toughness decrease, while the ultimate tensile strength and hardness increase with increasing CR reduction. This is attributed to increase of the hardening of the investigated ADI with cold

deformation processes (deformation bands and twins) and deformation - induced martensite. It must be mentioned that the observed changes in the mechanical properties at light cold deformation (7% reduction) are mainly attributed to the hardening of this alloy by plastic deformation concentrated in γ_r . At this light deformation the amount of mechanically formed martensite is very small (Fig. 5) [11].

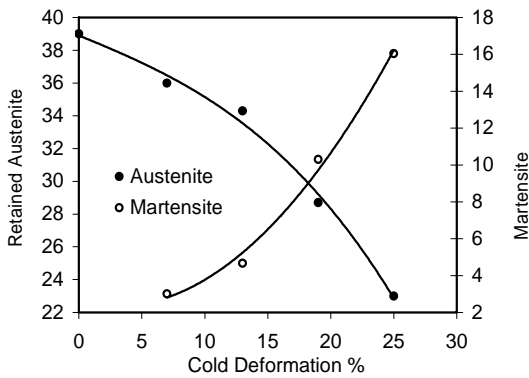


FIG. 5 VARIATION OF VOLUME FRACTIONS OF RETAINED AUSTENITE AND MECHANICALLY FORMED MARTENSITE WITH COLD REDUCTION PCT. [11]

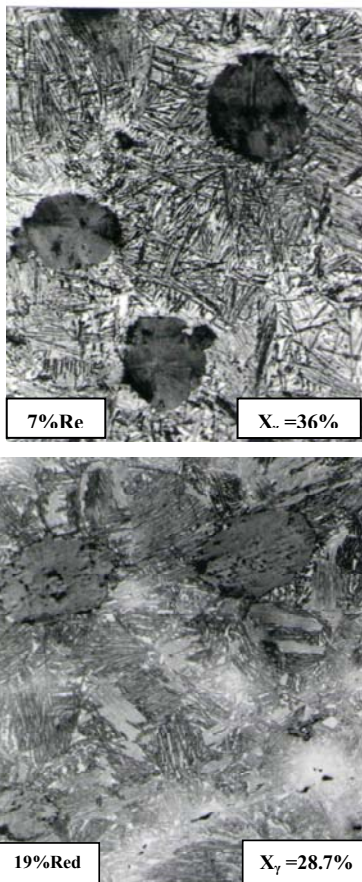


FIG. 6 MICROSTRUCTURES OF ADI AFTER TWO DIFFERENT REDUCTIONS SHOWING MARKED DECREASE OF γ_r AT 19% REDUCTION [12]

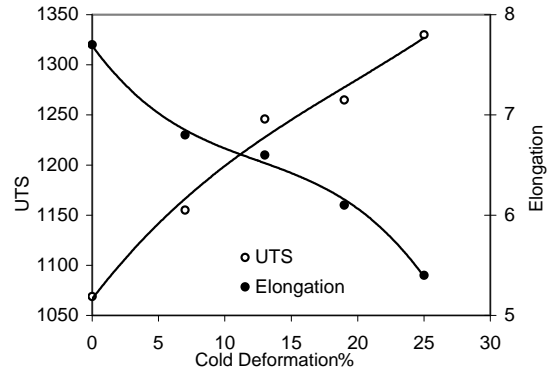


FIG. 7 VARIATION OF ELONGATION AND ULTIMATE TENSILE STRENGTH WITH COLD REDUCTION PCT

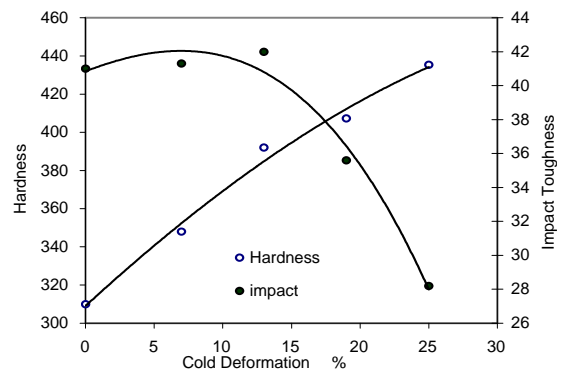


FIG. 8 VARIATION OF VICKERS HARDNESS AND IMPACT TOUGHNESS WITH COLD REDUCTION PCT

Good wear resistance is usually obtained in any material by ensuring a high hardness. Low austempering temperatures (235-250°C) produce hard ADI (~480-550 BHN) and such grades would be selected when good wear resistance is the main requirement. As the austempering temperature increases, the hardness decreases, resulting in more wear. However, the softer grades of ADI (typically 280-320 BHN) contain large amounts of austenite and this can work harden and/or transform to martensite when subjected to mechanical strain at the surface, with wear resistance significantly better than would be expected. Although this effect is a disadvantage when machining, it can be very beneficial for certain ADI components, since as the surface is worn away, it is continuously replaced by a freshly formed, hardened layer.

With increasing applications of ADI as a substitute for forged steels in manufacturing industries, strain hardening of ADI is attracting more attention and more research is required for better understanding of this phenomena. This may be attributed to the following factors:

- ADI components such as transmission gears, crackshafts, train car wheels are subjected to extensive machining during manufacturing and the strain-hardening behavior of ADI has profound influence on machining tool life and part surface finish.
- In many applications, ADI components undergo substantial plastic strains (e.g. fatigue, wear). The total life cycle of those components are, therefore, influenced by the strain-hardening characteristics of the material.
- Strain-hardening of the ADI matrix causes strain-induced martensite formation and this contributes to the high wear resistance of ADI.

The following discussion will attempt to report the extensive efforts made over the last few years to optimize the machinability, strength, and toughness and abrasion resistance of ADI. The novel applications associated with these developments will be shortly discussed.

Machinable ADI

When ADI first started to be used for engineering applications, there were many difficulties experienced in trying to machine it, and some of these doubtlessly persist to this day. The hardest grades of ADI reach a hardness of ~50 HRC which would pose a challenge for any high volume machining operation. Although the softer grades of ADI have a typical hardness of 300-350 BHN, their matrix structure contains up to 40% retained austenite. When subjected to strains in service, as was mentioned in section (3) of this survey, this phase rapidly work hardens and can transform to martensite [12,17,18], this can thereby reduce the machinability compared with a steel of equivalent hardness. The volume fraction of high carbon austenite present in the microstructure of austempered ductile iron (ADI) is one of the important factors that influence the mechanical and physical properties of the alloy. Formation of martensite by TRIP (transformation induced plasticity) mechanism during the machining operation, in which a large amount of stress is applied to the microstructure, results in decrease in machinability of ADI. It is considered that the limited use of ADI for high volume applications is partly due to machining difficulties. This was one of the motivations in the recent developments of a machinable ADI [19-26].

A lack of experience of the high volume machining of ADI adds uncertainty to the costs and production rates

and the early experiences of ADI exposed some inconsistencies in the machinability. These problems, however, can be minimized by collaboration between a knowledgeable foundryman, heat treater and machining expert.

The influence of austenitizing and austempering temperatures on the machinability of ADI was recently reported [27,28]. The production of machinable ADI has attracted the attention of many researchers in the last few years by optimizing the composition and heat treatment cycles of cast iron. Muhlberger developed [19] and patented [20] a machinable grade ADI by careful selection of the composition (low Mn) and heat treatment variables and this development was exploited in at least one European foundry [21,22]. More recently, two other grades of machinable ADI have been developed in the US [23,24], specifically aiming at increasing the use of ADI for automotive applications such as chassis components and crankshafts.

There are some differences between the two approaches, but the common feature is that the matrix structure contains a considerable amount of ferrite in both cases. The new grade, referred to as MADI™ is claimed to have unique machining characteristics and lower machining costs than as-cast ductile iron or regular ADI under appropriate conditions of speed and feed. In-plant machining trials have shown that MADI at 243 BHN could be machined on existing machine lines designed for ductile iron grade 65-45-12.

In a continuing effort to address the deficiencies of regular ADI, extensive efforts have been recently made to develop the dual-phase (ferritic-ausferritic) grades of ADI with enhanced machinability properties to compete with forged steel for power train applications [29-36]. The properties of dual phase matrix (DPM) ADI have been the subject of extensive studies [37-48].

ADI offers an excellent compromise between the values of proof stress and elongation; both are very highly appreciated in the field of suspension parts in the automotive industry [49]. Many potential uses of ADI in competition with forged steel and aluminum alloys can be opened due to strong possibilities of weight and volume reductions.

A car steering knuckle, which has high safety requirements, is a new potential application for ADI, where the impact resistance is the principle criterion determining part size and design.

TABLE 1 POINTS OF IMPROVEMENT [33]

		FDN	ADI	Mixed Structure
Tensile strength	MPa	510	1060	700
Proof stress (0.2%)	MPa	380	725	550
Elongation	%	14.5	14.5	14.5
Hardness	HB	207	321	250
Machinability		+++	+	++
Impact (Charpy)	J/cm ²	140	180	160
Deflection (drop)	mm/kJ	38	21	30

The main advantage in using ADI is a question of weight and cost. Ferritic ductile iron (FDI) is less expensive than forged steel but requires heavier sections due to its lower strength. Replacement of FDI with ADI results in 30% improvement of energy absorbed, but the plastic deformation becomes lower. Higher deformations are required for suspension parts, in particular for legal purposes in a context of accident and hence there has been a real interest to produce ADI with enhanced ductility properties.

Recently [33], a new ADI was suggested with optimal ductility through the development of dual-phase microstructures (ferrite-ausferrite or ferrite-martensite) by the proper heat treatment. Such dual phase (duplex) microstructures are obtained by intercritical annealing (partial austenitization) in the ($\alpha + \gamma +$ graphite) region followed by austempering at 250-400°C, and hence, colonies of proeutectoid ferrite are introduced within an ausferrite matrix. Superior strength-ductility combination was achieved in ADI with duplex microstructure compared with conventional ductile irons. Moreover, tensile strength and elongation of ferritic ductile iron (FDI) could be doubled in a ferrite-ausferrite duplex ADI. Such irons were also found to exhibit superior mechanical properties to those exhibited by ductile irons with ferrite-martensite matrices. Recently, an attempt was made to investigate the effect of alloying elements Ni, Mo and Cu on the properties of ADI produced by intercritical annealing and highest ductility (16%) and impact strength (145 J) were achieved in ADI alloyed with 1% Ni and 0.25% Mo [34-36]. The wear resistance of ADI's with dual matrix structures was found to decrease with the increase of proeutectoid ferrite and

decrease of ausferrite content [37]. The properties of the new mixed structure compared to both ADI and ferrite ductile iron (FDI) is shown in Table 1 [33], which emphasizes the main points of improvement.

- Replacement of FDI with ADI structure results in an improvement of tensile strength, yield strength and impact energy.
- Replacement of conventional ADI with that of a "mixed" structure leads, to hardness reduction (and hence better machinability) together with an increase in impact deformation. For an identical heat treatment cycle, the properties of ADI with "mixed" structure seem to effectively depend on the Si-content. The low-Si grade seems more attractive as it has tensile strength, proof strength, and hardness comparable with those of pearlitic structures with elongation and impact strength close to those of FDI. The higher strength values may be attributed to the more complete austempering transformation together with the absence of any pearlitic structure in the last to freeze zones. Moreover, the low Si-content reduces the hardening effect of Si on ferrite, which leads to significant deterioration of impact strength. The low Si type has higher impact energy than FDI and higher impact deformation than ADI [33].
- The ADI with the mixed (ferrite-ausferrite) structure provides a satisfactory solution where FDI does not have the necessary impact resistance or ADI does not provide the required deformation level or the required machinability.

Very limited research related to the strain-hardening characteristics of conventional ADI is available in the literature [10, 17]. Using the Holloman equation, the strain-hardening behavior of ADI subjected to a novel two-step austempering process was analyzed [50]. The strain hardening exponent values of ADI with two-step austempering process was shown to result in lower ductility and strain-hardening exponent values, compared to the conventional single-step austempering process. This result was related to the amount and morphology of microstructural constituents and the interaction intensities between carbon atoms and dislocation in the matrix. Recently [51], the strain hardening behavior of ADI with dual matrix structure (DMS) was investigated, it seems to be affected by the variations in the volume fraction as well as morphologies of phases, the degree of ausferrite connectivity and interaction intensities between carbon atoms and dislocation in the matrix.

It has been reported that fully ferritic (austenite free) ADI could be produced by austempering at 260°C and then tempered at 484°C for 2 hrs, without compromising the mechanical properties [52]. The process was rather sensitive to the austempering temperature, initial austempering at 385°C and tempering at the same temperature of 484°C resulted in a drastic reduction in the ductility and fracture toughness of the material. The machinability, however, was improved in both cases. Further development in this direction may lead to considerable enhancement of the machinability properties of ADI.

Enhancement of Strength Properties of ADI

Ausformed Austempered Ductile Iron (AADI)

It has been shown [5,53] that the rate of ferrite formation during stage I austempering may be controlled by the following processing variables:

- **Chemical** - including alloy content selection for hardenability purposes together with the austenitization temperature selection which controls the matrix carbon content.
- **Thermal** - including austempering temperature and time.
- **Mechanical** - including mechanical deformation introduced into the austempering schedule just after quenching, but before any substantial transformation of austenite (ausforming) (Fig. 9).

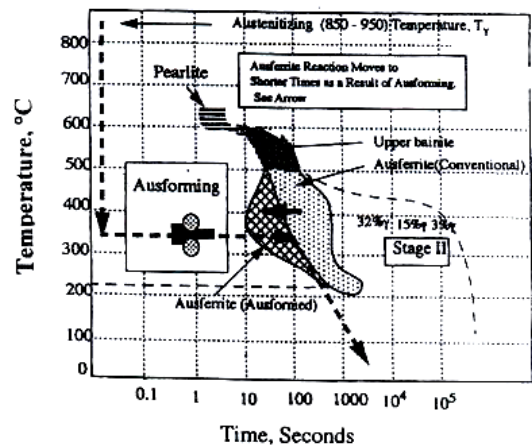


FIG. 9 SCHEMATIC REPRESENTATION OF THE AUSFORMING PROCESS [5]

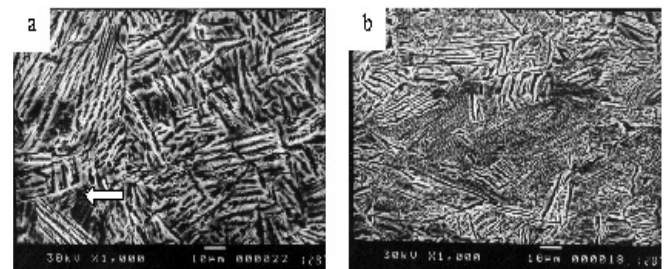


FIG. 10 SEM MICROGRAPHS OF ADI ALLOYED WITH 2% NI AUSTEMPERED AT 375°C FOR 1 MINUTE. (A) CONVENTIONALLY PROCESSED; (B) AUSFORMED TO 25% REDUCTION. ARROWS INDICATE THE BRITTLE MARTENSITE FORMED IN MANY ZONES IN THE CONVENTIONALLY PROCESSED ADI [53]

Naturally, an optimum final microstructure could be produced by including elements of all three processing variables. It has been shown [57-60] that mechanical processing of ADI can act as a control valve for the stage I austempering reaction. In ausformed austempered ductile iron (AADI), mechanical deformation is utilized to affect the microstructure and, consequently, the mechanical properties of ductile iron due to acceleration of ausferrite reaction, refining the microstructure and increase of the structural homogeneity.

A recent work [57] has shown that ausforming up to 25% reduction in height during a rolling operation contributed to add a mechanical processing component to the conventional ADI heat treatment, thus increasing the rate of ausferrite formation and leading to a much finer and more homogeneous ausferrite product (Fig. 10). The effect of ausforming on the strength values was quite dramatic (Fig. 11) (up to 70 and 50% increase in the yield and ultimate strength respectively). A mechanism involving both a refined microstructural scale as a result of enhanced ferrite nucleation together with an elevated dislocation

density was suggested [21]. Hardenability elements such as Ni and Mo are usually added to increase hardenability of thick section castings, and ausforming to higher degrees of deformation was found necessary to alleviate the deleterious effects of alloy segregation on ductility [58].

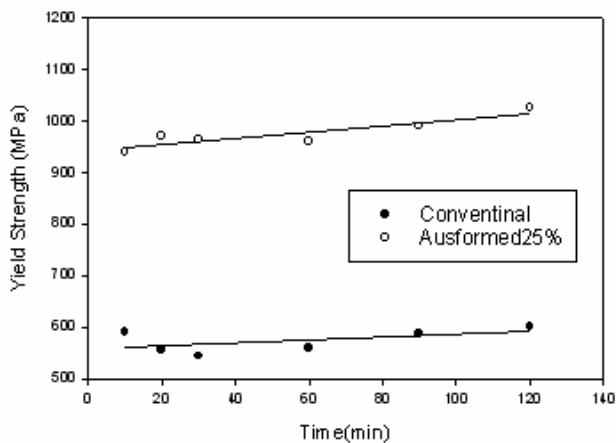


FIG. 11 YIELD STRENGTH VS AUSTEMPERING TIME AND AUSFORMING REDUCTION FOR ADIS ALLOYED WITH 2% NI.

It is more practical that the advantage of ausforming would be taken by forging rather than by rolling. The forging process may be performed on cast preforms, austenitized and quenched to the austempering temperature, inserted into a die, pressed or forged to the final shape and then returned back into the austempering bath to complete the accelerated transformation. Minimal deformation degrees by conventional forging standards, i.e. an average strain of 25% would be sufficient for the forming part of the processing sequence. It has been reported [59] that in situations where very severe deformation occurs, the work-piece may not need to be returned to the austempering bath to complete the transformation to ausferrite, as the latter will have been completed by the time the work-piece is extracted from the die.

The idea of creating preforms in ductile iron and then ausforming them to final shape could be quite effective for relatively simple shaped castings that must meet high demanding strength and ductility requirements, e.g. connecting rods for automotive applications. It is understood that certain deviations in design elements of both preform as well as the die set should be involved compared to the design of conventional ADI process. The abovementioned concept has been utilized to produce tank track center guides [60] using a finite element simulation technique to match both the preform design and the die design so that a uniform equivalent strain throughout the

casting averaged ~20%. No inclination - to fracture or cracking has been reported.

Squeeze Casting of ADI

ADI was produced without an austenitizing step based on a patent published in 1985 by P.B. Magalhaes [61]. In this process, casting in a permanent mold allowed the ejection of the part at a temperature level above 850°C where a completely austenitic range could be guaranteed. Subsequent quenching in a salt bath would lead to the ADI ausferritic microstructure.

Based on this process, a novel technique has been simultaneously developed at TU-Aachen Foundry Institute [62] and component CPC - Finland [63] to produce superior quality ADI castings, using squeeze casting of molten metal in permanent mold, followed by in-situ heat treatment of the hot knock-out casting in the austenite range, followed by normal austempering in a salt bath. Figure 12 shows a schematic representation of the process [62].

This technique seems to have some unique advantages, such as:

- Sound castings can be produced without feeders or gating system as the solidification expansion was used to counteract solidification shrinkage.
- Increased heat transfer avoids formation of macro- and micro-segregation, which decreases the mechanical properties of ADI.
- Chemical composition of ductile iron can be selected to avoid any metastable solidification in spite of the extremely fast solidification.
- The production process is shorter and less energy consuming as the elimination of sand from the process would allow the hot castings coming out from the permanent mold to be directly introduced to the heat treatment furnace.
- The structure of the SQ ADI is much finer (the graphite as well as the ausferrite), which means better mechanical properties (ultimate tensile strength, elongation and fatigue strength).
- The casting surface is entirely free from any surface defects, which again means higher fatigue strength.
- The machinability is better.
- More environmentally friendly.

TABLE 2 SOME TENSILE TEST RESULTS OF SQUEEZE CAST TEST SAMPLES COMPARED TO EN STANDARD [63]

	Test 1	EN	Test 2	EN
Tensile strength, MPa	1238	1200	1115	1000
Yield strength, MPa	968	850	839	700
Elongation, %	13.4	2	15.3	5
Hardness, HB	388	340/440	363	300/360

TABLE 3 COMPARISON OF DIFFERENT SUSPENSION FORK MATERIALS [63]

	GJS-600-5	SQ ADI (Tested)	Microalloyed Steel
Tensile strength, MPa	600	950	1000
Yield strength, MPa	370	750	550
Elongation, %	10	11	12

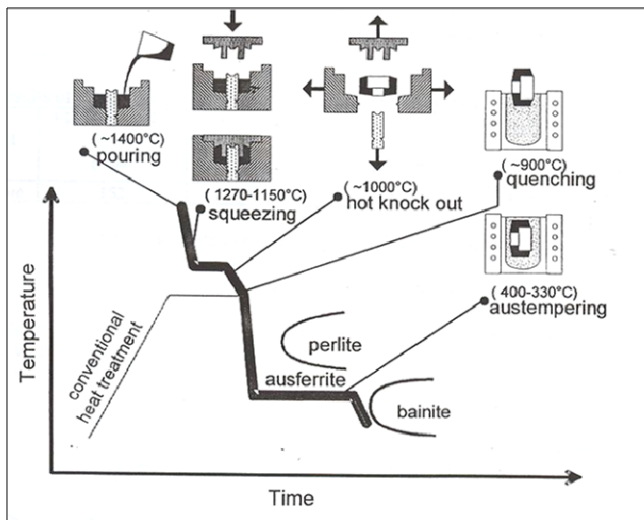


FIG. 12 PROCESS STEPS AND TEMPERATURE REGIME OF THE SQ PROCESS AND THE IN-SITU HEAT TREATMENT [62]

Table 2 [63] shows some tensile test results of a squeeze casted ring gear test samples compared to EN standard. Fiat suspension fork was tested for fatigue strength and amazing results were achieved. This component had to pass the test without cracks loaded with 250 KN after lifetime of 300,000 cycles. The squeeze cast forks could pass the test with 5000 KN without failure up to 3-10 million cycles. The tensile properties were much higher than pearlitic ductile iron or even better than microalloyed steels as shown in Table 3 [63], yield strength was much higher than steel and elongation about the same.

Two-step Austempering of ADI

The mechanical properties of ADI are mainly dependent on:

- The fineness of ferrite and austenite in ausferrite
- The austenite carbon (X_{γ}, C_{γ}) where:
 X_{γ} is the volume fraction of austenite
 C_{γ} is the austenite C-content

Both these factors depend on the austempering temperature. Higher undercoolings enhance the nucleation of ferrite from the parent austenite and hence promotes finer ausferrite structure with higher yield and tensile strength but lower ductility. On the other side, higher austempering temperatures result in coarser feathery ferrite and austenite with lower strength but higher ductility properties. Moreover, higher austempering temperatures lead to higher (X_{γ}, C_{γ}) parameter which, in turn, increases fracture toughness and fatigue strength of ADI.

It is possible, therefore, to optimize the mechanical properties of ADI by ausferrite refinement as well as increasing the austenite carbon. Hence, the novel concept of two-step austempering was conceived [64], which involves first quenching the alloy to a lower temperature (250-270°C) after austenitization, thus increasing the undercooling, and then, once the nucleation of ferrite is complete, immediately raising the temperature of the quenching media to a higher temperature to enhance faster diffusion of carbon and increase austenite carbon (X_{γ}, C_{γ}) in the matrix. A schematic of this process is shown in Fig. 13.

The two-step austempering process has resulted in higher wear resistance in ADI compared to the conventional single-step austempering process. An

analytical model for the abrasion wear behavior of ADI revealed the dependence of wear behavior of ADI on the microstructural parameters, especially the parameter $X_{\gamma}C_{\gamma}/\sqrt{d}$ where d is the ferritic cell size as well as the strain hardening exponent (n -value). The major wear resistant mechanism in ADI was shown to be the microstructural refinement in ausferrite and solution strengthening effect (high C-content in austenite) along with strain hardening effect of the austenite phase [65-66].

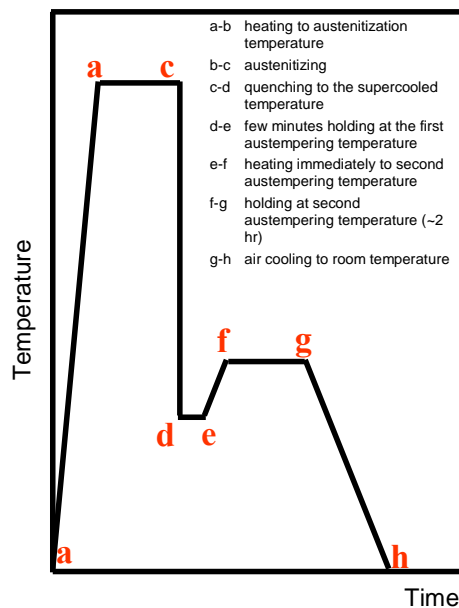


FIG. 13 SCHEMATIC OF THE TWO STEP AUSTEMPERING PROCESS

Meanwhile, the two-step austempering process resulted in higher crack growth rate and lower fatigue threshold than the single step ADI process. The crack growth rate increment due to the two-step austempering process increases with the austempering temperature [67]. Moreover, it has been shown in a recent publication carried out at (CMRDI) that the two-step austempering process increases the fracture toughness of ADI, where the increment in the fracture toughness by the two-step process is more pronounced in unalloyed irons [68].

The improved toughness was correlated to reduced ferrite grain size, increased carbon content of the retained austenite as well as its stability [33].

ADI with Enhanced Wear Resistance

Carbide ADI (CADI)

CADI is ductile iron containing carbides that is subsequently austempered to produce an ausferritic matrix with an engineered amount of carbides. Volume fraction of carbides may be controlled by

partial dissolution during the subsequent austenitization process and hence the proper abrasion resistance/toughness combination may be reached. CADI exhibits excellent wear resistance and adequate toughness. The abrasion resistance of this new material is superior to that of the ADI and increases with increased carbide content. In a number of wear applications, it can compete favorably with high Cr-abrasion resistant irons with improved toughness [69-76].

Several methods have been suggested to introduce carbides to the structure of ADI [38-40].

- (a) As cast carbides can be introduced to the structure of ADI through alloying with carbide promoting elements such as Cr, Mo, Ti, etc., controlling the cooling rate during solidification, adjusting the carbon equivalent to produce hypoeutectic composition or through surface chilling.
- Recently, it has been reported that good balance between wear resistance and impact toughness could be achieved through the selection of Cr-content/austempering temperature combination [69].
- (b) Carbides precipitated during austempering: extending the second stage austempering will result in the precipitation of fine carbides from the high carbon austenite: $\gamma_{HC} \rightarrow \alpha + \epsilon$.
- (c) Mechanically introduced carbides; crushed M_xC_y carbides are strategically placed in the mold cavity at the desired location. The metal then fills in around the carbides resulting in a continuous iron matrix with discrete carbides mechanically trapped. This method allows the engineer the option of placing carbides only where needed resulting in conventional ductile iron matrix throughout the rest of the casting. These particular carbides are essentially affected by subsequent austempering process. This technique is currently only practiced by license to Sadvik corporation and the specific method used to contain the carbides "in place" during mold filling needs further investigation.
- (d) Fully or mostly ferritic matrix is hard face welded in the area of greatest wear, which results in a carbide weld and a heat affected zone at the weld/casting interface. Subsequent austempering heat treatment has little or no effect on the weld structure, depending on the

TABLE 4 PROSPECTS AND POTENTIALS OF CADI [69]

Advantages	Risks/Disadvantages	Market Opportunities
<ul style="list-style-type: none"> • CADI is more wear resistant than grade 5 ADI with acceptable toughness • CADI is less expensive and tougher than 18% Cr-white irons • No capital investment is required for the foundry to add this new product 	<ul style="list-style-type: none"> • CADI exhibit only limited machinability – possibly grinding only • If alloying is used, the returns must be segregated • Additional operation and costs may be incurred if carbides are cast-in 	<ul style="list-style-type: none"> • Replaces Mn-steel at equal or lower cost • Replaces 18% Cr white iron at lower cost
Potential Applications		
Automotive Agricultural Railroad Construction and mining General industrial	Camshafts and can followers Rippers, teeth, plow points, wear plates and harvester Contact suspension components and railcar/hopper car wear plates Digger teeth and scarifiers, cutters, mill hammers, guards, covers, chutes, plates, housings, transport tubes and elbows, rollers crusher rollers Pump components, wear housings and plates, conveyor wear parts, skids and skid rails, rollers and blast parts	

chemical composition of the weld material chosen, whereas the heat affected zone is eliminated and a fully ausferritic matrix results in all areas except the weld area itself. In some weld applications, powdered metal carbides can be purged into the molten weld to provide additional wear resistance [69].

The advantages, disadvantages, market opportunities as well as potential applications of CADI are illustrated in Table 4 [69].

Bainitic/Martensite (B/M) Dual-phase ADI

A new grade of wear resistant ductile iron, with properties similar to those of ADI was recently developed by combining less expensive alloying with a controlled heat treatment to produce a bainitic-martensitic dual-phase structure. Alloying elements such as Si and Mn promote bainitic transformation were added in the range of 2.5-3.0% each. Moreover, such alloying facilitates the separation of bainitic transformation from martensitic one. Manganese significantly reduces the Ms temperature, dissolves unlimitedly into austenite and improves hardenability. At Mn-contents higher than 3.0%, austenite increases on the account of bainite and carbides starts to precipitate. Manganese carbides formation is restrained effectively by silicon, which promotes the formation of bainitic ferrite and the enrichment of austenite with carbon. The resulting increase in austenite stability will reduce the possibility of

manganese carbides formation and manganese dissolves in austenite and ferrite. The pearlite formation is avoided by controlled cooling heat treatment; consisting of three stages:

- (1) Water spraying quenching is applied for rapid cooling from austenitization temperature to about 300°C in a few minutes which suppress any pearlite transformation.
- (2) Soaking in a heat preservation setting for bainitic transformation over a range of temperature forms the spraying end temperature to 200°C for 2 hrs.
- (3) Air cooling to room temperature for martensitic transformation.

The resulting microstructure containing bainite, martensite and 8-10 vol. % retained austenite along with the graphite spheroids will give an excellent combination of hardness and toughness which reach 51.5 HRC and 21.7 J/cm² respectively and this could be attributed to the following factors [77,78]:

- i) The bainite needles split the unde-compensated austenite and effectively decrease the size of martensite leading to improved strength and toughness.
- ii) High toughness of bainite restricts the propagation of cracks originating mainly at the graphite/matrix interface and hence toughens the iron.

- iii) The presence of retained austenite (8-10 vol. %) contributes to the toughening effect.

The impact wear resistance of the B/M ductile iron was found to be comparable with that of the high chromium cast iron and twice that of manganese steel. Under conditions of low impact load, such as that in the case of grinding balls and liners in the small and medium diameter ball mills, the B/M ductile iron can replace the manganese steel as a wear resistant material. In such application, the B/M ductile iron shows good work-hardening effect due to the presence of the retained austenite. The surface work-hardening effect can considerably improve the wear resistance of the hardened surfaces, while the core of the balls remains tough.

Currently, there is an increasing interest [79] in the as-cast austenite-bainite ductile iron, produced by alloying with >3.0% Ni, and up to 0.8% Mo and up to 1.0% Cu. The tensile strength and elongation of the as-cast alloyed ductile iron were shown to be higher than those of irons subjected to hot-shake-out from sand molds at 250°C and held for two hours. The inferior properties in the second case were attributed to the increased levels of retained austenite.

Thin-Wall ADI Castings

To achieve fuel economy in automotive industry, reducing the vehicle weight has been a major research area of interest over the last few decades. Although the general trend has been to use low density materials (aluminum, magnesium and composites) instead of cast iron and steel in the automotive industry, numerous examples have been recently noted in the literature where iron castings started again to replace aluminum in the industry. This comparison is encouraged by the increased strength, ductility, stiffness, vibration damping capacity, as well as reduced cost [80]. If the yield stress/cost ratio of the various materials is compared, the new member of the ductile iron family, the ADI, is most of the time the winner. When mechanical properties, density and cost are included in material evaluation, ductile iron may offer more advantages than aluminum, particularly if thin wall ductile iron parts could be produced without further heat treatment processes. The potentials for ductile iron applications for lightweight automotive components have been limited by the capability to produce as-cast free thin wall parts (2-3 mm) [81,82]. Production of thin-wall ductile iron castings still represents a daily challenge in modern foundries.

Review of the recent literature shows that thin-wall ductile iron has been successfully produced for many years, thanks to the optimization of some critical production parameters: pouring temperature, chemical composition, thermal conductivity of the molding materials, type and amount of inoculating material in combination with the spheroidizing method adopted, casting design and other foundry basic practices [83,84].

When the commercial introduction of ADI in 1972, consistent efforts have been made to identify new applications of this new emerging material, however, difficulties have been encountered in producing ADI thicker than 100 mm due to the segregation of hardenability elements added to prevent pearlite formation. Such difficulty in obtaining the required austemperability and the heterogeneous microstructures do not represent a real problem when producing thin wall ADI castings due to the insignificant segregation tendency associated with rapid solidification of those thin wall castings. The use of ADI in thin-wall and high strength parts has, however, been mentioned in a very limited number of reference [85,86]. Successful case was recently reported [85], where a hollow connecting rod for a two-cylinder car engine and a front upright for a racing car were successfully made of thin wall ADI, which confirms the capability of ADI to build complex thin walled parts of high strength. With recent development in inoculation theory and practice, it became possible to cast thin-wall ductile iron parts completely free from carbides. Consequently, further improvements in the properties of thin wall ADI castings could be achieved with the austempering process. In a recent study [87], the results of a R&D program on the effect of wall thickness (3-10 mm) and silicon content (2.4-2.7%) on the properties of ADI has been reported. It has been shown that thin-wall ADI castings austempered at 360°C and containing low silicon can exhibit ultimate strength exceeding 1100 MPa with more than 10% elongation. This is an indication that austempered thin-wall ductile iron is becoming a logical choice for the production of small, light weight and cost effective automotive components. However, more data about the metallurgy of thin-wall ADI castings seems to be of practical interest.

Recently [88], 2 mm ADI plates with a homogeneous ausferritic and nodule count of 300 nodules/mm² were produced at CMRDI. It was found that decreasing the wall thickness leads to reduced amounts of retained

austenite and structure refinement, which in turn increase the hardness. Increasing the austempering temperature from 350°C to 400°C resulted in reduced tensile strength values (950 and 1000 MPa for 8 and 2 mm wall thickness, respectively) to (775 and 875 MPa for the same wall thickness), increased impact strength (from 40 to 80) and from 100 to 125 J at wall thicknesses of 2 and 8 mm, respectively, apparently due to increased amounts of retained austenite at higher austempering temperatures.

Concluding Remarks

1. Extensive research work over the past decade has helped to develop the property combination of ADI in three directions:
 - increased strength, ductility and toughness
 - enhanced wear resistance/toughness combination
 - improved machinability
2. ADI offers high levels of mechanical properties at a competitive cost. When the high strength of ADI is taken into account, it could successfully compete with lightweight alloys, as the additive weight required to give unit strength is lower. Moreover, when the relative cost of ADI required to give unit strength is considered, ADI seems to be one of the cheapest alloys. These points have yet to be fully appreciated by many design engineers. Currently, novel processing techniques adopted to achieve better strength and toughness properties include ausforming, cold-rolling, two-step austempering, squeeze casting and others.
3. The current research work aiming at improving machinability of ADI looks rather vital for the future of this material. The available machining techniques required for forging steel are not always suitable for ADI components, particularly on a high volume machining line dedicated to the production of one specific product. This problem can be minimized with the development of ferritic or ferritic + ausferritic ADI structures.
4. Carbide as well bainitic/martensitic ADI offer opportunities for superior wear resistance, combined with reasonable toughness, which may open new applications for ADI.

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